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Advanced Control in Smart Microgrids

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CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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List of Symbols

C	Filter capacitance [μF]
D_i	Switching state of phase i (i = a, b, c) leg of the IGBT bridges
f_1, f_2, f_{11}, f_{22}	Slopes or derivatives
f_g	Grid frequency [Hz]
$\boldsymbol{i}_f$, $\boldsymbol{i}_L$, $\boldsymbol{i}_g$	Filter current, load current, and grid current [A]
$\boldsymbol{I}_{\mathrm{d}}$	Current through the diode [A]
$\boldsymbol{I}_{\mathrm{PV}}$	Photocurrent of the PV cell [A]
$\boldsymbol{I}_{\mathrm{s}}$, $\boldsymbol{I}_{\mathrm{r}}$	Stator and rotor phase current vectors [A]
K_p, K_i	Gain constant of the Proportional-Integral (PI) controller
L	Line inductance [mH]
L_{m}, R_{m}	Magnetizing inductance and resistance per phase [Ω]
$L_{\sigma\mathrm{s}}$, $L_{\sigma\mathrm{r}}$	Stator and rotor phase winding leakage inductance [Ω]
L_{s}, L_{r}	Stator and rotor phase winding self-inductance [Ω]
L_t	Tie-line inductance [mH]
m, n	Droop coefficients [rad/W, Wb/Var]
N	Coincidence point
P_1, P_2	Active power injected by DGs to microgrid [W]
P_L	Active load power [W]
P_g	Active power injected by utility to microgrid [W]
P_{rated}, Q_{rated}	Active and reactive power rating of the DGs [W]
P_{s}, Q_{s}	Stator active and reactive power [W]
p	Number of pole pairs
Q_1, Q_2	Reactive power injected by DGs to microgrid [Var]
Q_L	Reactive load power [Var]
Q_g	Reactive power injected by utility to microgrid [Var]
R	Line resistance [Ω]
R_{L}	Load resistance [Ω]
R_{PVs}, R_{PVsh}	Intrinsic series and shunt resistances of the PV cell [Ω]
R_{s}, R_{r}	Stator and rotor phase winding resistance [Ω]
R_t	Tie-line resistance [Ω]

Sk	Sector division
T_c	Computing time [μs]
T_e	Electromagnetic torque [Nm]
T_s	Sampling period [μs]
T_V	Virtual torque [Nm]
V_{dc1}, V_{dc2}	DC source voltage of the Distributed Generation [V]
$\boldsymbol{V}_i$, $\boldsymbol{V}_c$, $\boldsymbol{E}$	Inverter voltage, capacitor voltage, and load-side voltage [V]
V_g	Magnitude of the grid voltage [V]
$\boldsymbol{V}_s$, $\boldsymbol{V}_r$	Stator and rotor phase voltage vectors [V]
ω_1, ω_r, ω_s	Synchronous, rotor, and slip angular frequency [rad/s]
ω_c	Cut-off angular frequency [rad/s]
ω_g	Grid angular frequency [rad/s]
$\boldsymbol{\psi_s}$, $\boldsymbol{\psi_r}$	Stator and rotor flux vectors [Wb]
$\boldsymbol{\psi}_V$, $\boldsymbol{\psi}_E$	Inverter flux vector and load-side flux vector [Wb]
φ_{fV}, φ_{fE}	Phase angles of the inverter flux and load-side flux [rad]
φ_V, φ_E	Phase angles of the inverter voltage and load-side voltage [rad]
φ_Z	Phase angles of the line impedance [rad]
δ	Phase angle difference between inverter flux and load-side flux [rad]
λ	Leakage coefficient
λ_2, λ_3	Weighting factors

List of Abbreviations

ADC	Analog to Digital Conversion
ALS	Average Load Sharing
AMI	Advanced Metering Infrastructure
BDFTSIG	Brushless Doubly Fed Twin Stator Induction Generator
CHP	Combined Heat and Power Stations
3C	Circular Chain Control
CSCF	Constant Speed Constant Frequency
CSI	Current Source Inverter
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAC	Digital to Analog Conversion
DFC	Direct Flux Control
DFIG	Doubly-Fed Induction Generator
DG	Distributed Generation
DPC	Direct Power Control
DSP	Digital Signal Processor
DTC	Direct Torque Control
ESS	Energy Storage System
FACTS	Flexible Alternating Current Transmission Systems
FRT	Fault Ride Through
HVDC	High Voltage Direct Current Transmission Systems
ICT	Information Communication Technology
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IGCT	Insulated Gate Commutated Transistor
IPM	Intelligent Power Module
ISR	Interrupt Service Routine
LB	Load Bank
LPF	Low Pass Filter
MOMPC	Multi-Objective Model-Predictive Control
MPC	Model Predictive Control
MPDFC	Model Predictive Direct Flux Control
MPPT	Maximum Power Tracking Point

MS	Master-Slave
MT	Micro-turbine
NIST	National Institute of Standard and Technology
NPC	Neutral-point-clamped
PC	Personal Computer
PCC	Point of Common Coupling
PDPC	Predictive Direct Power Control
PDVTC	Predictive Direct Virtual Torque Control
PEMFC	Proton Exchange Membrane Fuel Cell
PI	Proportional-Integral
PMSG	Permanent Magnet Synchronous Generator
PV	Photovoltaic
PWM	Pulse Width Modulation
RTDX	Real Time Data Exchange
SCADA	Supervisory Control and Data Acquisition
SCIG	Squirrel Gage Induction Generator
SDFC	Switching Table Based Direct Flux Control
SDPC	Switching Table Based Direct Power Control
SGA	Smart Grid Australia
SOC	State of Charge
SPI	Serial Peripheral Interface
SPWM	Sinusoidal Pulse Width Modulation
STATCOM	Static Synchronous Compensator
STS	Static Transfer Switch
SVM	Space Vector Modulation
REIF	Renewable Energy Integration Facility
RF	Radio Frequency
THD	Total Harmonic Distortion
TSR	Tip Speed Ratio
UART	Universal Asynchronous Receiver Transmitter
UPS	Uninterruptible Power Supply
UTS	University of Technology, Sydney
VC	Vector Control
VOC	Voltage-Oriented Control

VSCF	Variable Speed Constant Frequency
VSI	Voltage Source Inverter
WFSG	Wound Field Synchronization Generator

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ABSTRACT

This thesis presents various advanced control strategies in smart microgrid applications.

In recent years, due to the rapid depletion of fossil fuels, increasing demand of electricity, and more strict compulsory government policies on reduction of greenhouse gas emissions, renewable energy technologies are attracting more and more attentions and various types of distributed generation (DG) sources, such as wind turbine generators and solar photovoltaic (PV) panels, are being connected to low-voltage distribution networks. Because of the intermittent nature of the renewable energy sources, it would be a good idea to connect these DG units together with energy storage units and loads to form a local micro power system, known as microgrid. This PhD thesis project aims to develop new and competitive control methods for microgrid applications.

Based on a review of the state of the art of the wind power techniques, a new predictive direct control strategy of doubly fed induction generator is proposed. This method can achieve fast and smooth grid synchronization, and after grid connection, the active and reactive power can be regulated flexibly, which enables the wind power systems contributing to the grid voltage support and power quality improvement. The proposed strategy is simple and reliable, and presents excellent steady-state and dynamic performance.

A new control approach using the model predictive scheme is developed for a PV system in microgrid applications. In the islanded operation, the inverter output voltage is controlled stably for the local loads. A simple synchronization scheme is introduced to achieve seamless transfer, and after being connected to the utility grid, the PV system can inject both active and reactive power into the grid flexibly within its capacity.

As the capacity of DGs getting larger, the power conversion efficiency becomes more important. In order to reduce the switching loss, a multi-objective model-predictive control strategy is proposed for the control of high power converters. By revising the cost function properly, the switching frequency can be reduced considerably without deteriorating the system performance. The control strategy is simplified using a graphical algorithm to reduce the computational burden, which is very useful in practical digital implementation where high sampling frequency is required. The proposed method is very flexible and can be employed in both AC/DC and DC/AC energy conversions in microgrids.

For a microgrid consisting of several DG units, various system level control methods are studied. A novel flux droop control approach is developed for parallel-connected DGs by drooping the inverter flux instead of drooping the inverter output voltage. The proposed method can achieve autonomous active and reactive power sharing with much lower frequency deviation and better transient performance than the conventional voltage droop method. Besides, it includes a direct flux control (DFC) algorithm, which avoids the use of proportional-integral (PI) controllers and PWM modulators.

For a microgrid system consisting of a 20 kW PV array and a 30 kW gas microturbine, a coordinated control scheme is developed for both islanded and grid-connected operations. The experimental results from a renewable energy integration facility (REIF) laboratory confirmed the feasibility of the control strategy. The response of this microgrid under the condition of grid faults is investigated and the relevant protection mechanism is proposed.

Given the intermittent nature of the renewable energy sources, and the fluctuated load profile, an appropriate solution is to use energy storage systems (ESS) to absorb the surplus energy in the periods when the power production is higher than the consumption and deliver it back in the opposite situation. In order to optimize the power flow, a model predictive control (MPC) strategy for microgrids is proposed. This method can flexibly include different constraints in the cost function, so as to smooth the gap between the power generation and consumption, and provide voltage support by compensating reactive power during grid faults.